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Atmos. Chem. Phys. Discuss., 5, 12617–12639, 2005
www.atmos-chem-phys.org/acpd/5/12617/
SRef-ID: 1680-7375/acpd/2005-5-12617
European Geosciences Union

Atmospheric Chemistry and Physics Discussions

An unusual stratospheric ozone decrease linked to isentropic air-mass transport as observed over Irene (25.5° S, 28.1° E) in mid-May 2002

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Received: 14 September 2005 – Accepted: 31 October 2005 – Published: 7 December 2005

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Abstract

A prominent ozone minimum of less than 240 Dobson Units (DU) was observed over Irene (25.5° S, 28.1° E) by the Total Ozone Mapping Spectrometer (TOMS) during May 2002 with extremely low ozone value of less than 219 DU recorded on 12 May, as compared to a climatological mean of 249 DU for May between 1999 and 2005. In this study, the vertical structure of this ozone minimum is examined using ozonesonde measurements performed over Irene on 15 May 2002, when the total ozone (as given by TOMS) was about 226 DU. Indeed, it is found that the ozone minimum is of Antarctic polar origin with a low-ozone layer in the middle stratosphere above 625 K and of tropical origin with low-ozone layer between 400-K and 450-K isentropic levels in the lower stratosphere. The upper and lower depleted parts of the ozonesonde profile for 15 May, are respectively attributed to equatorward and poleward transport of low-ozone air toward the subtropics. The tropical air moving over Irene and the polar one passing over the same area associated with enhanced planetary-wave activity are simulated successfully using a high-resolution advection contour model (MIMOSA) of Potential Vorticity. Indeed, in mid-May 2002, MIMOSA maps show a polar vortex filament in the middle stratosphere above the 625-K isentropic level and they show also tropical air-masses moving southward (over Irene) in the lower stratosphere between 400-K and 450-K isentropic levels. The winter stratospheric wave driving and its associated localized isentropic mixing leading to the ozone minimum are investigated by means of two diagnostic tools: the Eliassen-Palm flux and the effective diffusivity computed from the European Center for Medium-range Weather Forecasts (ECMWF) fields.

The unusual distribution of ozone over Irene during May 2002 in the middle stratosphere is closely connected to the anomalously pre-conditioned structure of the polar vortex at that time of the year. Indeed, the perturbed vortex was typically predisposed for easy erosion by dynamical transport processes, which have been driven by strong planetary wave activity and have eventually resulted in a very large latitudinal advection of polar air masses towards the subtropics. The exceptional presence of polar vortex

air over the subtropics during May 2002 can be considered as the first sign of the particular polar vortex disturbances, which after being well reinforced, contributed to the unprecedented behavior of the Antarctic spring ozone hole observed during September 2002.

1. Introduction

Tropical ozone is a prominent actor in atmospheric chemistry and physics and the tropical Southern Hemisphere latitudes are among the best locations for detecting a possible recovery of the ozone layer. However tropical ozone studies that rely only on satellite measurements are not able to neither resolve vertical-fine scale structures nor completely inform our understanding of both photochemical and dynamic processes that are operating in the atmosphere and contributing to the ozone budget. The sparseness of in-situ measurements in the tropical and subtropical Southern Hemisphere has limited investigations of ozone distribution and variability related to atmospheric dynamics and climate, e.g., the meridional transport, the varying position of the Intertropical Convergence Zone (ITCZ), the Quasi-Biennial Oscillation (QBO), the El Niño-Southern Oscillation (ENSO) and La Niña. Against this background, the Southern Hemisphere Additional Ozonesondes (SHADOZ) project was initiated in 1998 to increase the ozonesonde launches at tropical and subtropical latitudes. Irene (25.5° S, 28.1° E) in South Africa became part of the SHADOZ network in October 1998 and ozonesonde launches have continued on a bimonthly basis up to the present day. Situated in the subtropical region, Irene represents a location of major interest for the observation of low and high latitude influences attributed to transport processes. Thompson et al. (2003a, b) used 1100 SHADOZ radiosondes from 10 southern tropical and subtropical sites during the 1998–2000 period to characterize the seasonality and variability in ozone. They showed that the total amount of ozone is generally low in the tropics in winter. Their data also show higher stratospheric ozone at Irene due to a greater frequency of mid-latitude air passing over the site. In their classification of tropospheric

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ozone profiles over Johannesburg based on MOZAIC (Measurement of Ozone and Water Vapor aboard Airbus In-service Aircraft) data, Diab et al. (2003) showed that source regions over continental central Africa and long-distance transport are responsible for the mid-tropospheric peak in summer and the low-tropospheric enhancement in spring. In their climatology of the tropospheric ozone based on ozonesonde measurements over Irene, Diab et al. (2004) noted that the seasonal features over Irene are modulated by both tropical and mid-latitude influences because of its location on the boundary of zonally-defined meteorological regimes. Bencherif et al. (2003) used lidar aerosol data measured over Durban (29.9° S, 31.0° E, South Africa) during the period 21 April to 14 June 1999, to stress the importance of horizontal transport of air masses from the tropics towards the subtropics and mid-latitudes across the southern subtropical barrier in the lower stratosphere. In their case study of 12 July 2000, using ozone soundings performed from Reunion Island (20.8° S, 55.5° E), Portafaix et al. (2003) reported on a strong isentropic exchange between the mid-latitudes and the tropical stratosphere. Brinksma et al. (1998) presented an analysis of low ozone values during the 1997 winter in the mid-latitudes (New Zealand), which they attributed to the northward and southward meridional transport. Logan et al. (2003) presented a full analysis of the Quasi-Biennial Oscillation (QBO) in tropical ozone using SHADOZ measurements, supplemented by satellite profile and column data derived from SAGE II and Total Ozone Mapping Spectrometer (TOMS) measurements. Using a middle atmosphere circulation model, Horinouchi et al. (2000) showed that the transport between the tropics and the extratropics is strongly dependent on altitude and has geographic preferences in the lower stratosphere with the existence of lateral privileged routes in northern hemisphere during winter. All these previous studies dealt explicitly with the influence of the horizontal exchange between the mid- and high-latitudes on one side, and tropics and subtropics on the other side on the distribution and variability of stratospheric ozone.

In the present paper a high-resolution advection contour model (MIMOSA) of Potential Vorticity and dynamical diagnosis tools, are used to investigate the basic dynamics

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behind an unusual ozone decrease observed over Irene.

The dilation of the polar vortex edge, which is due to a linear propagation of Rossby waves leads to irreversible non linear mixing at lower latitudes in the surf zone, where the horizontal gradients in Ertel Potential Vorticity are small (Teitelbaum et al., 1998). An unusually weak polar vortex was an exceptional feature of the entire winter of 2002, which pre-conditioned it for a progressive dilation. This was associated with distinctive persistent stratospheric vacillations starting in the early winter 2002 (Scaife et al., 2005). This behavior of the wintertime polar vortex was considered to be the main perquisite for the development of the first major sudden stratospheric warming recorded in September 2002 (Journal of Atmospheric Sciences, Special Issue, Vol. 62, No. 3). This major warming, which has never been observed before over the Southern Hemisphere since its discovery by Scherhag (1952) induced a splitting into two parts of the Antarctic ozone hole. Many studies have focused on the major sudden stratospheric warming of September 2002 and on the separation of the ozone hole into two pieces (Varotsos, 2002, 2003a, b, 2004; Allen et al., 2003; Hio and Yoden, 2005; Krüger et al., 2005; Manney et al., 2005; Newman and Nash, 2005; Roscoe et al., 2005). However, the early-winter pre-conditioning anomalies and their impact on the subtropics have been little documented and studied.

The present paper reports on an unusual event characterized by an ozone decrease in mid-May 2002, over Irene a subtropical site, in connection with planetary-wave activity increase, polar vortex filament excursions up to subtropical latitudes in the middle stratosphere and tropical air-masses presence in the lower stratosphere over the same area.

The data and analytical tools used in this study are described in Sect. 2. In Sect. 3, we will characterize the May 2002 ozone anomaly by the use of 7 years of TOMS and ozonesonde data. The dynamical processes are investigated in Sect. 4. Conclusions are presented in Sect. 5.

2. Data and analysis

In this section, a brief overview of the ozone and meteorological data along with the diagnostic tools used for the analyses is given.

2.1. Ozone data

The 1998-2005 ozone profiles for Irene (25.5° S, 28.1° E, South Africa) used in this study have been performed by the SAWS (South African Weather Service) and are archived on the SHADOZ (Southern Hemisphere Additional Ozonesondes) web site (http://croc.gsfc.nasa.gov/shadoz) (Thompson et al., 2003a, b). For the present study, 178 profiles measured fortnightly between November 1998 and May 2005 were used. More precisely, in order to examine the early winter state of stratospheric ozone over Irene, we focused our analysis on the May ozone concentration profiles measured during the period from 1999 to 2005. In addition, total ozone columns over Irene for the same period were taken from the TOMS experiment on board the Earth Probe satellite (data available at NASA/Goddard Space Flight Center web site: http://toms.gsfc.nasa.gov/ozone), which provides daily global distribution of ozone with a resolution of 1° in latitude and 1.25° in longitude.

2.2. Diagnosis tools

2.2.1. The Ertel potential vorticity, the Eliassen-Palm flux and the effective diffusivity

The diagnostic tools used in this paper: the Ertel Potential Vorticity (Epv), the Eliassen-palm (E-P) flux and the effective diffusivity, were computed from the ECMWF reanalyses. In fact, the Potential Vorticity (PV) on isentropic surfaces behaves as a dynamical tracer in the absence of diabatic effects, and is well adapted to study isentropic transport across dynamical barriers: polar vortices or subtropical barriers (Hoskins et al., 1985; Holton et al., 1995; Bencherif et al., 2003). In addition, the E-P flux and the effective diffusivity have been used as diagnostic tools in a number of studies of atmospheric data and numerical models of specific dynamical phenomena. Indeed, on one hand, the E-P flux vector and its divergence show a clear picture of planetary-wave propagation from the troposphere into the stratosphere and mesosphere (Eliassen and Palm, 1961; Andrews et al., 1983, 1987; Kanzawa et al., 1984). On the other hand, the effective diffusivity K_{eff}, presented as a function of equivalent latitude, is a powerful and elegant tool for the characterization of the large-scale isentropic mixing (Nakamura, 1996; Haynes and Shuckburgh, 2000a, b; Allen and Nakamura, 2001, 2003; Tan et al., 2004; Morel et al., 2005). K_{eff} provides a measure of the mixing properties of a flow. Indeed, K_{eff} shows low values nearby dynamical barriers (vortices and subtropical barriers). High values of K_{eff} are associated to strong mixing.

2.2.2. The MIMOSA advection transport model

In order to investigate the contribution of the horizontal transport mechanism in the vertical distribution of ozone over subtropics, we have used the MIMOSA (Modélisation Isentrope du transport Méso-échelle de l'Ozone Stratosphérique par Advection) high-resolution advection contour model. MIMOSA advection model of PV was developed at Service d'Aéronomie by Hauchecorne et al. (2002). The model runs on an orthogonal grid covering the whole Southern Hemisphere with a resolution of 3 grid points/degree. Epv at each grid point is advected using ECMWF winds and the advected fields are re-interpolated on the original grid every 6 h (Morel et al., 2005).

3. Ozone observations over Irene in May 2002

This section is designed to characterize an extreme ozone event in the stratosphere observed during May 2002 over Irene. The specific date of May 15 of our study is chosen by matching particularly low ozone events identified from Earth Probe TOMS records with a coinciding ozonesonde flight over Irene.

Daily total ozone values derived from TOMS records for years between 1999 and 2005 are depicted for the month of May in Fig. 1. As shown by the dashed horizontal line on the figure, the monthly averaged total ozone over Irene location is 249±12 DU (at 1σ). The absolute minimum total ozone (219 DU) which is about 30 DU less than the May climatological mean is obtained on 12 May 2002. As for the coincident day of ozonesonde flight (on 15 May), the corresponding total ozone (226 DU) is also significantly less than the climatological mean. In fact, one notices that the negative anomaly of total ozone persists for more than a week (see Fig. 1).

The mid-May vertical distribution of stratospheric ozone over Irene as obtained from ozonesonde measurements is illustrated in Fig. 2. It shows the ozone concentration profile (solid line) recorded on 15 May, together with the monthly mean profile (dashed line). The later is obtained similarly as for the TOMS total ozone mean, i.e. by averaging together all the May ozone profiles (over 16 ozonesondes flown fortnightly from 1999 to 2005).

The ozone profile recorded on 15 May 2002 (Fig. 2, solid line) shows strong negative deviations in comparison with the 7-year (1999–2005) mean profile for May (dashed line) between 400-K and 450-K in the lower stratosphere and above the 625-K potential temperature level in the middle stratosphere. This suggests that the total ozone decrease reported from TOMS data in the early winter of 2002 (mid-May) and depicted in Fig. 1 may be related to the (very) low concentrations of ozone at isentropic levels between 400-K and 450-K and at those greater than 625 K (Fig. 2).

4. Isentropic transport and the mid-May 2002 ozone minimum

The aim of this section is to investigate the role of isentropic transport of tropical and polar air masses, in conjunction with an increase in planetary-wave activity and the induced isentropic mixing, to contribute to the extreme ozone reduction event observed in early winter 2002 in the subtropics (Irene).

4.1. Tropical and polar air mass advection toward the subtropics

In order to investigate tropical and polar air-mass transports toward the subtropics, high resolution PV-maps on selected isentropic surfaces were constructed for 4–15 May using the MIMOSA advection model.

Figure 3 shows snapshots of PV advected by MIMOSA (APV) on the 440-K (lower stratosphere) and on the 675-K (middle stratosphere) isentropic surfaces for selected days prior to and during the ozone minimum event. The tropical and polar air-masses can be identified respectively by low and high absolute APV values. On each APV-map, the location of Irene is indicated by a black spot. On 4 and 8 May (upper APV maps on plate (b) of Fig. 3), at the 675-K isentropic surface, Irene is covered by air-masses of relatively low absolute APV values, while on 12 and 15 May, a tongue with high absolute APV indicating air of polar origin is deformed and shifted away from the pole toward the subtropics. It extends over the 15–120° E longitude and 20–40° S latitude range, covering a large area over the south part of Africa, including Irene. In parallel, on 4 and 8 May (upper APV maps on plate (a) of Fig. 3), at the 440-K isentropic surface, Irene is covered by air-masses of relatively high absolute APV values, while on 12 and 15 May, a tongue with low absolute APV indicating air of tropical origin, has moved eastward and southward toward subtropics.

Nearly the same transport situations are obtained from MIMOSA outputs for selected isentropic surfaces in the 625–800 K (middle stratosphere) and 400–450 K (lower stratosphere) ranges (not shown). This is in agreement with the vertical extension of the negative deviation observed on the ozone concentration profile recorded on 15 May for θ-levels higher than 625 K and those between 400 K and 450 K (see Fig. 2).

Because of polar vortex disturbances, MIMOSA analyses show how polar air-masses were injected into mid-latitude regions and sporadically into the subtropics. Moreover, this large latitudinal extension (from pole to subtropics) goes simultaneously, in a reverse way, with isentropic transport of tropical air-masses towards the mid-latitudes in the lower stratosphere. This episode of horizontal exchange between the tropical stratospheric reservoir and mid-latitudes is there again well identified on MIMOSA APV-maps during the period from 10–18 May (not shown). This is in agreement with the time extension of the minimum of total ozone derived from TOMS measurements (see Fig. 1).

Thus, the unusual reduction of total ozone observed over Irene by mid-May 2002 seems to be related to isentropic transport of air-masses simultaneously in the lower and upper stratosphere, respectively from the tropics to the mid-latitudes and from the pole to the subtropics.

It is a particularly interesting situation. In the lower stratosphere (400–450 K) the ozone profile (Fig. 2) shows a tropical influence. Indeed, ozone concentrations there are significantly under climatological values and similar to the tropical values (Portafaix et al., 2003). As for the low concentrations of ozone in the upper part of the profile (above 625 K), they can be attributed to air-mass advection from pole to tropics due to the fact that there is less ozone in the polar region.

4.2. Wave activity and isentropic mixing

A perturbed polar vortex is associated with enhanced planetary wave activity, which contribute to pull out materials from the vortex and distribute filaments equatorward (Schoeberl et al., 1988, 1992). Moreover, in the stratosphere nearby a subtropical barrier the isentropic mixing has been linked to disturbances occurring at the vicinity of the polar vortex in the winter hemisphere (Waugh, 1993). The transport of polar air toward low latitudes occurs in the form of a polar filament. This transport can have different effects depending on whether it is reversible or irreversible. If reversible, the effect is to perturb the ozone content at low latitudes for a limited period of time. If irreversible, polar air is mixed with the surrounding air.

The rapid and irreversible deformation of Epv contours on the 675-K isentropic surface observed in plate (b) of Fig. 3 suggests a planetary-wave breaking linkage resulting in quasi-horizontal mixing and irreversible tracer transport (McIntyre and Palmer, 1983, 1984).

Figure 4 shows E-P cross-sections computed using ECMWF fields, with arrows representing the E-P flux vectors, and contours, values of the wave driving, averaged over the period 3–8 May (Fig. 4a) and 11–16 May (Fig. 4b) and for the selected date of 15 May 2002 (Fig. 4c). Planetary-wave breaking is identified by the convergence of the E-P flux (i.e. negative wave driving in Fig. 4). The comparison between Figs. 4a and 4b shows an increase in stratospheric wave activity during the period from 11 to 16 May. In fact, strong upward wave propagation is located over high latitudes during that period of time (Fig. 4b). The E-P flux vectors bend equatorward with height and generate a large region of convergence over the subtropics in the stratosphere, where the wave driving reaches a minimum lower than $-6\,\mathrm{m.s^{-1}}$. The wave activity is particularly strong on 15 May 2002 (Fig. 4c) and is associated with a greater wave penetration and an enhanced wave driving in the subtropical middle stratosphere where the wave driving reaches a minimum lower than $-10\,\mathrm{m.s^{-1}}$ per day. This analysis demonstrates that, by early-winter 2002, planetary-wave activity has significantly increased during the mid-May period. It shows upward and equatorward planetary-wave trajectories.

Figure 5 shows values of the effective diffusivity K_{eff} calculated as described by Allen and Nakamura (2001, 2003) and by Morel et al. (2005). The state of mixing on the 700-K isentrope for the period April-May 2002 is summarised in Fig. 5 showing the time evolution of K_{eff} as a function of equivalent latitude. It shows a region of large K_{eff} between 10 and 20 May 2002 in the 20–30° S area. From the superimposed contours on Fig. 5 illustrating ECMWF zonal winds as a function of equivalent latitude, it can be seen that the southern stratospheric zonal circulation changed from easterlies to westerlies early, allowing the planetary waves to spread and bend equatorward nearby the subtropics (as shown by EP-flux on Fig. 4) and contributing to the increase in mixing. Indeed, one notices that mixing (K_{eff}) has increased in the 20–30° S equivalent latitude range by mid-May as underlined by the dotted circle.

Clearly, the early-winter dynamics of 2002 are directly responsible for the unusual ozone reduction observed over Irene in mid-May 2002. The large-scale transport and mixing of polar air-masses explains the decrease of stratospheric ozone over Irene and

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the strong negative deviations recorded in mid-May 2002 in Irene ozone profile when compared with the 7-year (1999–2005) mean May profile. Indeed, the polar vortex in the early winter of 2002 was unusually disturbed so that enhanced planetary-wave activity easily eroded it into filaments. This gave rise to large-scale transport of polar air toward the subtropics and largely contributed to the development of the low ozone episode over Irene in mid-May 2002.

5. Discussion and conclusion

In this paper we investigated the ozonesonde dataset obtained at Irene, a South-African subtropical site, as part of SHADOZ programme. The retrieved ozone concentration profiles were supplemented by daily TOMS total ozone columns derived for the same location and covering the same period, i.e., November 1998–May 2005.

A prominent ozone minimum has been reported in mid-May 2002 from TOMS and ozonesonde datasets. Combination of these datasets suggests that the most significant contribution to the total ozone reduction may be explained by low ozone concentrations obtained at isentropic surfaces higher than 625 K in the middle stratosphere and at those between 400 K and 450 K in the lower stratosphere. The absolute minimum of total O_3 (219 DU) was 30 DU (about 12%) less than the May mean value.

It was found from MIMOSA advected PV-maps that the observed ozone reduction over the subtropics (Irene) could be attributed to a transport of tropical and polar air-masses. From planetary-wave trajectories illustrated by EP-flux in Fig. 4, the large-scale transport polar air-masses was driven by an unusual increase of planetary-wave activity due to the early reversal of the zonal circulation followed by an increase of mixing near the subtropics (Fig. 5).

The present study demonstrated that the early-winter dynamics of 2002 was directly responsible for the unusual ozone reduction over the subtropics through large-scale transport and mixing of tropical and polar air-masses. Other extreme ozone minima over Northern and Southern Hemispheres have also been shown to also have dynamical origins (Brinksma et al., 1998; Hood et al., 2001; Grainger and Cordero, 2002; Semane et al., 2002; Hood and Soukharev, 2005). Recently the Journal of Atmospheric Sciences devoted a special issue on "the Antarctic winter and sudden warming 2002". Many studies have focused on the major sudden stratospheric warming of September 2002 and on the ozone hole split into two pieces (Varotsos, 2002, 2003a, b, 2004; Allen et al., 2003; Hio and Yoden, 2005; Krüger et al., 2005; Manney et al., 2005; Newman and Nash, 2005; Roscoe et al., 2005). Nevertheless, the early-winter pre-conditioning anomalies and their impact on the subtropics have been little documented and studied.

In fact, the early-winter 2002 ozone minimum and its large extension up to the subtropics represent an anomaly. It is closely connected to the unprecedented state of the southern polar vortex disturbances recorded during May 2002 as reported by Newman and Nash (2005).

Usually, the winter circulation at high southern latitudes is characterized by low planetary-wave activity and a strong polar vortex which is somewhat isolated from mid-latitudes (Cordero and Grainger, 1997).

To summarize, a 8–12% decrease in total column of ozone, concomitant with low-ozone concentrations in the middle stratosphere at isentropic levels above 625 K and in the lower stratosphere (400–450 K) observed over Irene in mid-May 2002, can be attributed respectively to ozone-poor air originally from the polar vortex and to ozone-poor air coming from tropics. This resulted in the lowest ozone column recorded during the 7-years period (1998–2005). MIMOSA advected PV-maps representing the early winter 2002 period in the middle stratosphere highlighted an unusually high planetary-wave activity and a disturbed polar vortex with filament excursions and strong mixing up to the subtropics in the middle stratosphere. In parallel, MIMOSA model simulated successfully the transport of a tropical poor-ozone air toward the subtropics in the lower stratosphere.

Acknowledgements. We are grateful to ECMWF for providing the meteorological fields. The TOMS data were produced and provided by the NASA Ozone Processing Team at Goddard Space Flight Center (http://toms.gsfc.nasa.gov/ozone). The ozone soundings data were provided by the Southern Hemisphere Additional Ozonesondes (SHADOZ) project (http://croc.gsfc.nasa.gov/shadoz).

The *Laboratoire de Physique de l'Atmosphère* (LPA) is supported by the French *Centre National de la Recherche Scientifique* (CNRS), the *Institut National des Sciences de l'Univers* (INSU), the *Conseil Régional de La Réunion* and the European Community (FEDER).

The present study is part of the 2005 French PNCA programme (*Programme National de Chimie Atmosphérique*).

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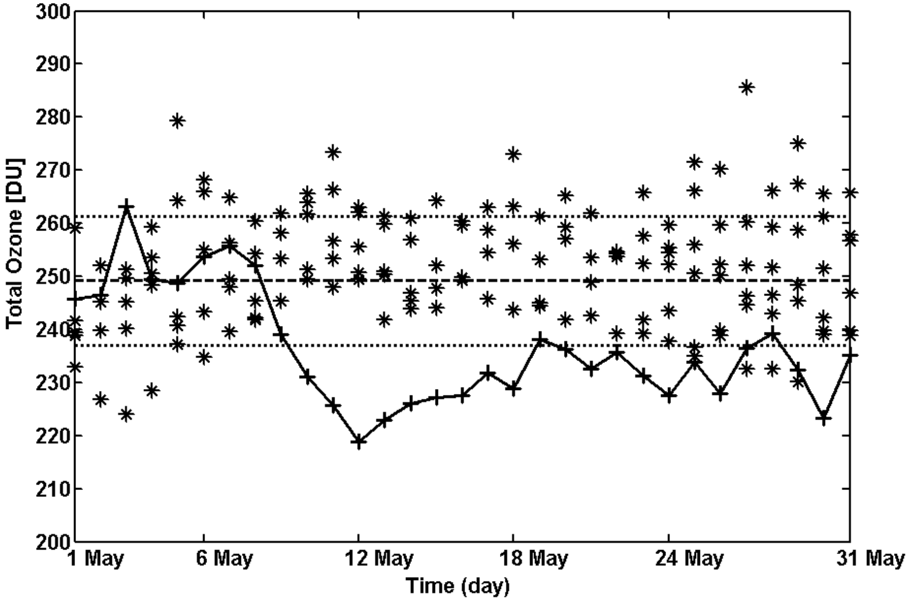

Fig. 1. Daily total ozone column (in DU) for May, over Irene, as derived from TOMS/Earth Probe Satellite overpass data for 2002 (solid line with '+' symbols) and for 1999–2005 ('$*$'). The horizontal lines represent the corresponding monthly mean value (dashed line) $\pm\sigma$ (dotted line).

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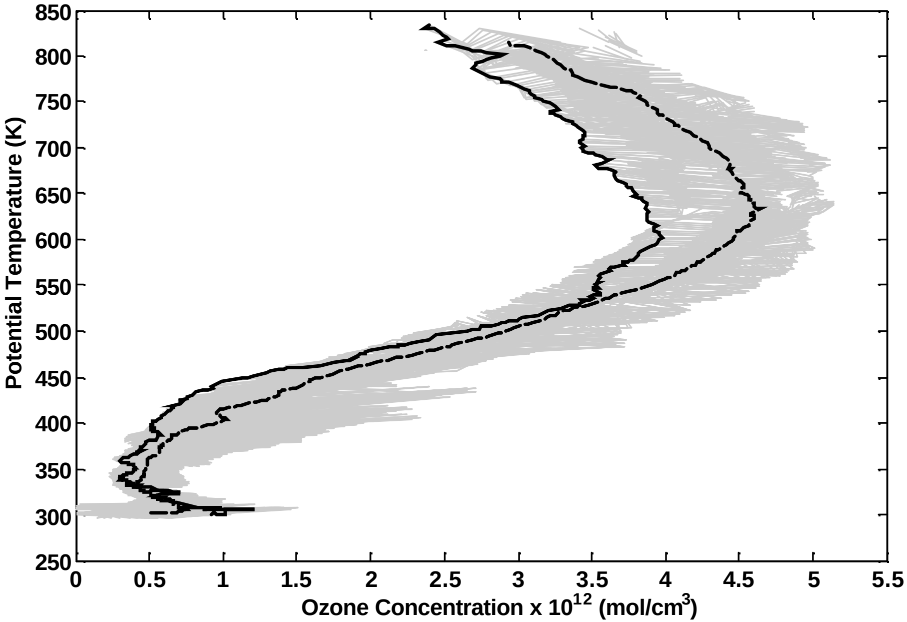

Fig. 2. Ozone concentration profile as obtained from ozonesonde measurements over Irene (25.5° S, 28.1° E) on 15 May 2002 (solid line) compared to the May profiles from 1999 to 2005 (in grey) and the corresponding mean profile (dashed line).

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Plate (a)

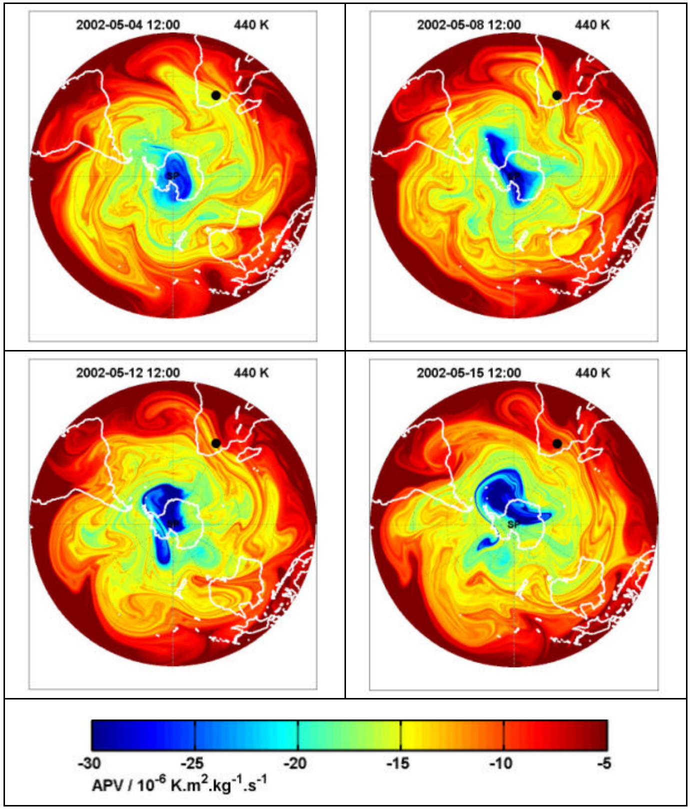
2002-05-04 12:00
440 K
2002-05-08 12:00
440 K
2002-05-12 12:00
440 K
2002-05-15 12:00
440 K
-30
-25
-20
-15
-10
-5
APV / 10^-6 K.m^2.kg^-1.s^-1

Fig. 3.

Plate (b)

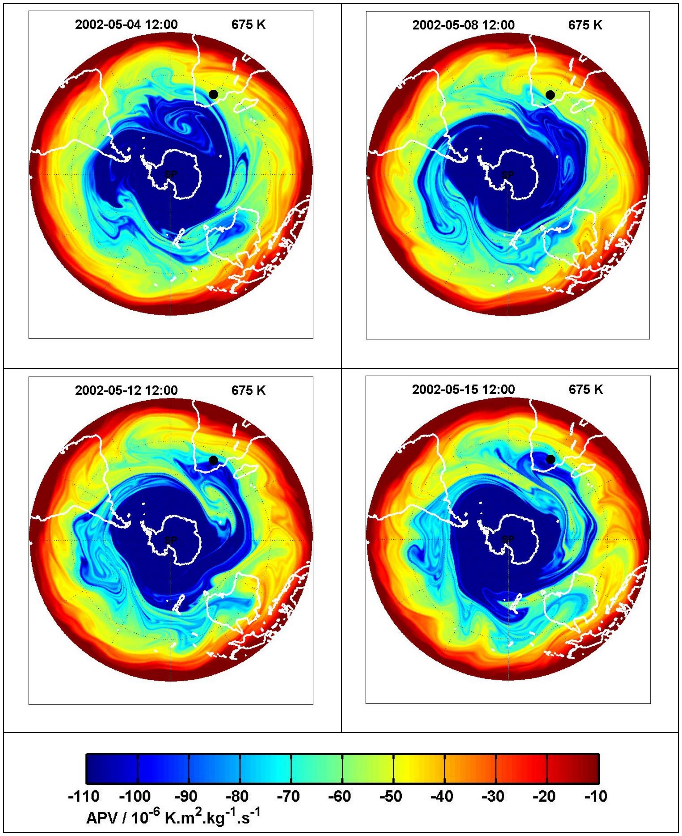

Fig. 3. Maps of Potential Vorticity (Epv) advected by the MIMOSA advection transport model. Plate **(a)** Outputs are calculated on the 440-K isentropic level for 4, 8, 12 and 15 May 2002 and Plate **(b)** Outputs are calculated on the 675-K isentropic level for 4, 8, 12 and 15 May 2002. Irene is indicated on each APV-map with a black spot.

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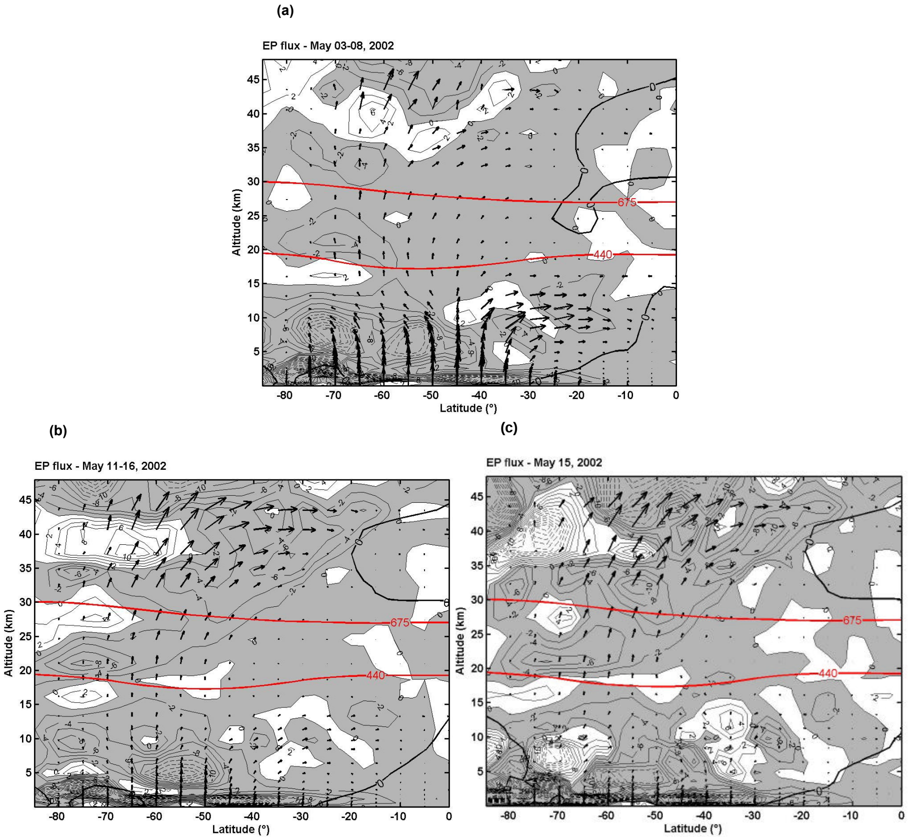

Fig. 4. E-P flux cross-sections in the meridional plane averaged over **(a)** 3–8 May, **(b)** 11–16 May and **(c)** for the selected day of 15 May 2002. Contours represent values of the wave driving, in m.s^{-1} per day; negative wave driving is shaded. The contour interval is 2 m.s^{-1} per day and dashed contours correspond to values more than 10 m.s^{-1} per day or less than −10 m.s^{-1} per day. The zero wind line has been overlaid (thick solid contour). The red lines indicate the isentropes 440-K and 675-K.

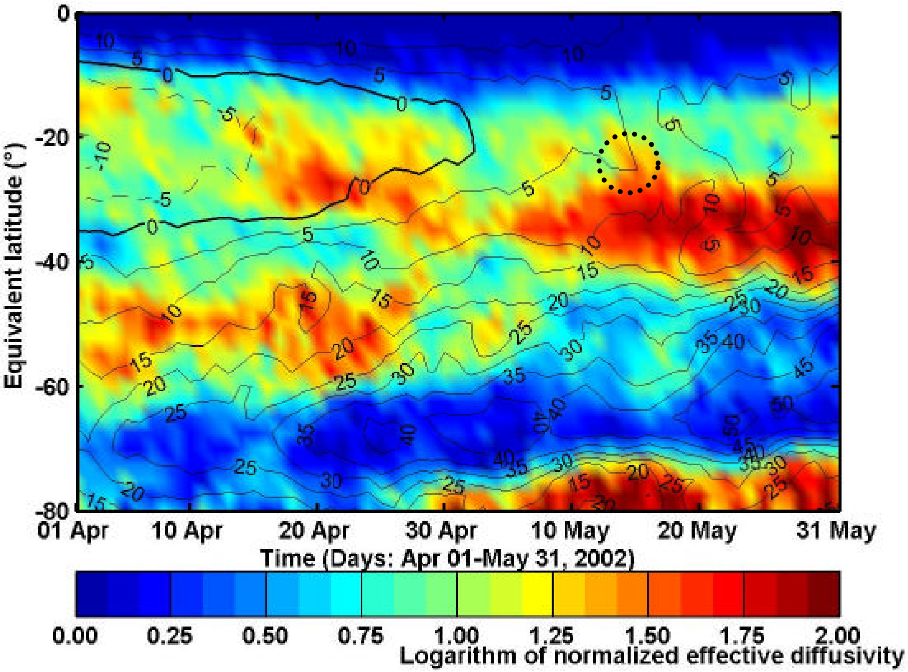

Fig. 5. Time-versus-equivalent latitude logarithm of normalized effective diffusivity on the 700-K isentropic level computed using ECMWF fields. The dotted circle indicates the exceptional latitude extent of high mixing, which reaches subtropics in mid-May 2002. Contours represent values of the ECMWF zonal wind, in m.s^{-1}; easterly winds are plotted with dashed contours while westerly winds are plotted with solid contours. The contour interval is 5 m.s^{-1}. The zero wind line is plotted with thick solid contour.

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